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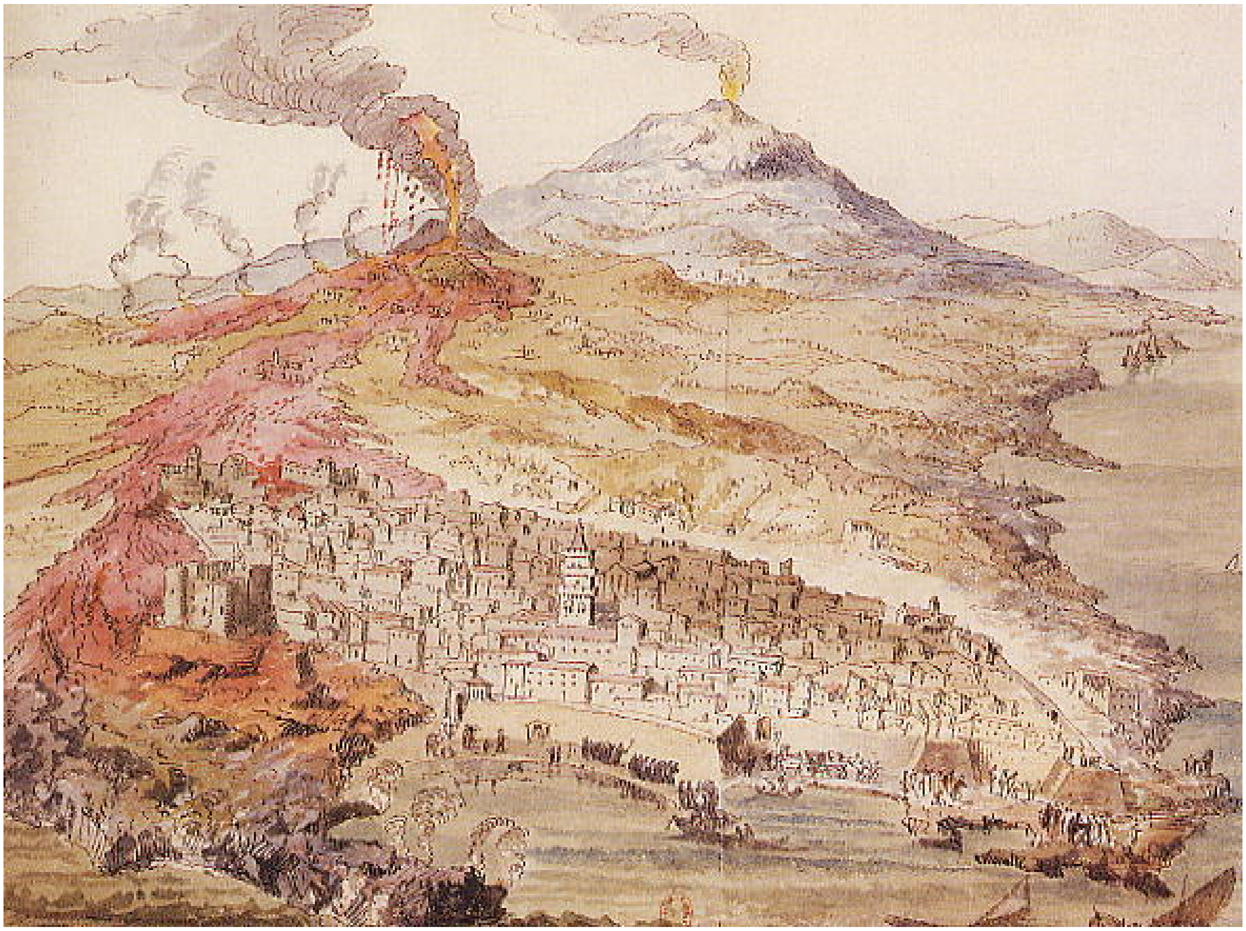
Lava Flows and Flow Fields



Destruction of Catania by lava flows during the 1669 eruption of Mt Etna in Sicily.

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Introduction

Lava flows are the most common volcanic feature on Earth. They provide fine construction materials and are also an essential source of nutrients for future agricultural soils. They nevertheless remain a persistent threat to human activity. After describing the primary features of lava flows, therefore, this chapter will focus on how such features can be used to improve forecasts of how a lava will behave.

On Saturday 18 March 1944, San Sebastiano was an unassuming Italian village in the foothills of Mount Vesuvius. On Tuesday 21 March, it ceased to exist. In less than 48 hours, lava streams from a new eruption had descended the volcano's flanks and crept through the village, slowly and inexorably eating their way from one building to the next. Today, five decades later, San Sebastiano is flourishing again as a popular residential area 10 km east of Naples. Yet the 1944 flows were the third set to have overwhelmed the settlement in less than 100 years. After both previous eruptions, in 1855 and 1872, the village and its neighbours were rebuilt around the very lavas that had caused their destruction. Not even the menace from Vesuvius could break the lure of the familiar.

The resilience, or perhaps stubborness, that keeps populations returning to hazardous districts is the chief reason why lava flows are a common threat to human settlements, even though they are produced by one of the least powerful styles of eruption. Between 1973 and 1998, lava effusions worldwide caused property losses of hundreds of millions of U.S. dollars (equivalent 1998 prices). Although these losses are small compared to those due to major explosive eruptions, they have long-lasting repercussions on local economies and are a key force driving investigations into how lavas behave and how defensive techniques can be improved.

A second motive for studying lavas is that they are the single most common feature on the surfaces of the terrestrial planets. They cover 90% of Venus, 50% of Mars, at least 20% of the Moon, and some 70% of the Earth, where they are mostly hidden from view on the ocean floor. Understanding how lavas are emplaced is thus crucial to reconstructing the surface evolution of the inner planets and to investigating the conditions below the surface that favour effusive eruptions.

The main factors controlling how lava flows develop are the rate at which lava is effused from the ground, the lava's physical properties, and the local environment (such as ground slope, topography and whether the eruption occurs on land, or below water or ice). Each of these factors can vary greatly among eruptions, as well as during a single effusion, and it might be expected that lavas should show a wide range of behaviour. In fact the contrary holds and common lava types evolve along only a few, clearly-defined trends, which link the morphology of lava surfaces to styles and rates of flow advance. Only by understanding why these natural evolutionary sequences occur will it be possible to improve strategies for mitigating lava hazard.

What are lava flows?

Lava flows are outpourings of molten rock, or magma. On Earth, the overwhelming majority have silicate compositions, for which common melting temperatures are in the range 800°-1200°C; lavas of sulphur (e.g., Siretoko-Iosan volcano in Japan, and Lastarria volcano in Chile) and of carbonate compositions (e.g., Ol Doinyo Lengai volcano in Tanzania) also occur at lower temperatures (about 150°C for sulphur and 600°C for carbonatite), but these are extremely rare and are not important as far as general hazard studies are concerned. First applied at Vesuvius, the word "lava" is derived from the italian *lavare* (to wash), ironic since the washing normally meant cleaning away the fruits of human labour.

Flows are distinguished from lava domes by their extreme elongation downslope. Historically, the volumes produced by single effusions of lava range from minor dribbles to outpourings of a few cubic kilometres (e.g., Etna, Sicily, 1614-24; Lanzarote, Canary Islands, 1730-36; Lakagigar, Iceland, 1783-85). The resulting flow fields can extend tens of kilometres, spread kilometres across and reach thicknesses of hundreds of metres, although most are more modest in size (Table 1). The durations of single eruptions also cover a large range and, while some may reach decades, the majority lie between days and months. Rates of flow lengthening thus rarely exceed a brisk walking pace, so that it is usually possible for people to escape immediate danger. Exceptions occur during the start of effusions, when lavas can sometimes advance as fast as a galloping horse. In the saddest example, on Nyiragongo (Congo) at 10.15 in the morning of 10 January 1977, a fluid lava swept downslope at least 5 km in 20 minutes (15 km per hour), catching a small village unawares and roasting 70 people alive.

The Nyiragongo tragedy ghoulishly illustrates the need to prepare against lava invasion even before an eruption begins. To identify the most vulnerable districts, it is necessary to recognise probable locations of future eruptions and to forecast the likely travel distance of at least the initial lava flow. The first task is achieved by applying statistical analyses to the known distributions of vents at a volcano. The second requires a model which can link probable flow length to factors that can be measured before the next eruption begins, and it is here that the evolutionary sequences of lava flows assume a fundamental importance.

Table 1. Major Historic Lava Flows

Composition	Typical Length (km)	Mean Thickness (m)	Mean Discharge Rate (m^3s^{-1})	Flow (& Flow Field) Volume (km^3)
SiO_2 < 55wt% (basalts, basaltic andesites)				
	< 10	3-20	10-100	0.01-0.1
	(basalts to 50)		(basalts to 1000)	(< 1-2)
e.g. Kilauea & Mauna Loa, Hawaii. Etna & Vesuvius, Italy. Iceland. Piton de la Fournaise, Réunion Is. Lanzarote & Tenerife, Canary Is. Arenal, Costa Rica. Parícutin, México.				
SiO_2 > 55wt% (andesites, dacites, trachytes)				
	< 5	20-300	1-10	0.01-1.0
	(some to 15)		(andesites to 100)	(< 10-20)
e.g. Lonquimay, Chile. Nea Kameni, Santorini, Greece. Hibok-Hibok, Philippines. Trident, Alaska.				

Evolutionary sequences among lava flows

Most lavas are crystallizing upon eruption, owing to chemical imbalances induced in magma as it approaches the surface from below. They continue to solidify during effusion, aided by loss of heat to the ground and to the atmosphere. As a result, flows begin to form channels or tubes (Figures 1 & 2) which concentrate motion along only a small number of paths, so that subsequent lava can be transported more efficiently from the vent to the front.

A flow initially forms a tube or a channel according to whether or not the lava surface can develop a continuous crust. When exposed to the atmosphere, a fresh lava surface chills to a strong, solid crust within minutes. At the same time, the new crust is pulled forward by more mobile lava. If the forward pull is large enough, the crust continually breaks into fragments and so, being unable to form a stable roof, the flow develops an open channel for containing the lava. If the forward pull is too small, a continuous crust can develop across the whole flow and this, anchored to the flow margins, gives birth to a tube.

A similar battle between crustal growth and disruption occurs at flow fronts. When disruption dominates, the front moves forward as a single unit, controlled by the properties of the frontal interior. When crust formation dominates, the front advances by oozing small tongues of lava through localised punctures in the crust. Whatever their style of motion, lava fronts are the slowest part of an advancing flow, in part because of crystallization, and in part because their areas of cross-section are larger than the active areas along feeding channels or tubes.

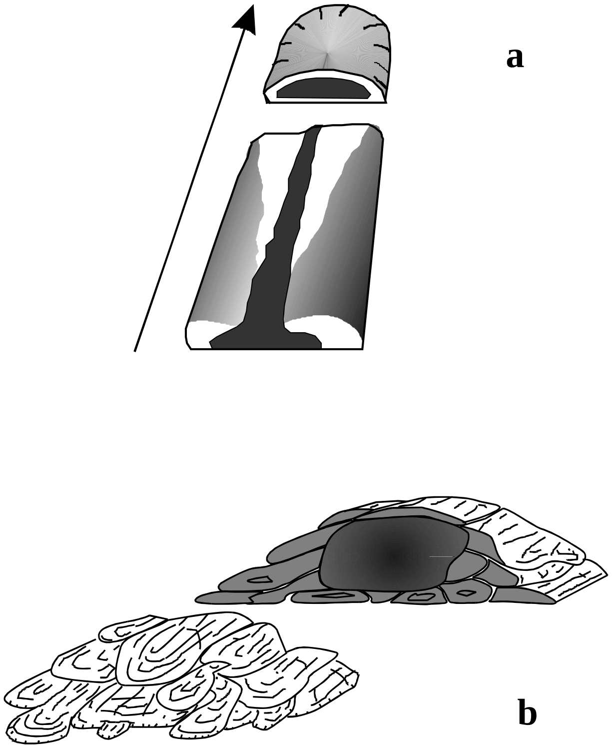


Figure 1. Major flow structures. *(a)* In aa and blocky flows, open channels (*below*) typically feed lava to simple fronts (*above*). Motion, in direction of arrow, is concentrated in the black zones. For major flows, the fronts are commonly ~100 m wide and tens of metres thick. In long-lived eruptions, the channels may evolve into tubes. (After Lipman and Banks 1987) *(b)* The fronts of pahoehoe flows are normally a complex of intermingling tongues and toes (up to metres across and tens of metres long) fed by lava from a tube system.

From observation alone, it is clear that crustal structure can be linked directly to the early formation of lava channels and tubes, and to the style with which a flow front moves forward. The link with crustal structure is convenient since only the outer parts of an active flow are normally accessible to investigate, either by direct observation on the ground or by remote monitoring using aircraft or satellites. Difficulties in studying the rest of a flow arise because lavas are hot and viscous. To measure the temperatures, velocities and fluidities of flow *interiors*, it is necessary to stand close to poorly-crusted lava, where it is easiest to insert monitoring equipment. The most active parts of flows have mean surface temperatures commonly between 475°C (when their colour is a very dull red) and 1100°C (when they are golden yellow), a range sufficient for radiant heat to cause serious burns even metres away. Protective clothing, although cumbersome, can normally overcome this difficulty. However, even at the start of eruption, the most fluid lavas are frequently a million times more viscous than water (Table 2) and it is extremely difficult both to force a measuring device into a flow and, if successful, to retrieve it again.

Figure 2. *(Left)* A well-developed channel between static banks of aa lava. This example is a few metres wide, but channel widths may reach tens of metres in aa and hundreds of metres in blocky flows. Note the haze due to hot gases (mostly steam) escaping from the lava, moving from left to right (Photo: C. R. J. Kilburn). *(Right)* Extensive lava tubes are essential features of pahoehoe flows and may also form in aa flow fields during long-lived eruptions (Photo: H. Pinkerton).

As a result, virtually no data are available from direct measurements of active lava interiors. Investigations must instead rely upon theoretical studies or upon indirect evidence from solidified lava interiors (exposed by natural collapse or by artificial excavations, such as road cuttings or quarries). In the first case, no theoretical model has yet been completely verified, precisely because the necessary field data are unavailable. In the second, the features preserved by solidified lava interiors (such as crystal size distributions, which depend on a lava's cooling history) may not reflect conditions that prevailed while the flow was still active, because these features (a) may have been dominated by changes (*e.g.*, further crystallization) which occurred after the flow had come to rest, or (b) may have formed at different times during flow advance, and so cannot simply be related to the state of the active flow at any particular moment. Thus, until more reliable data are available for active flow interiors, the links between crustal structure and flow dynamics offer the best prospect of quantifying flow behaviour.

Table 2. Physical Properties of Lava Flows

Composition	Eruption Temperatures °C	Density at Eruption Temperatures kg m^{-3} (without vesicles)	Viscosities at Eruption Temperatures Pa s*
Basalt	1050 - 1200	c. 2600 - 2800	$10^2 - 10^3$
Andesite	950 – 1170	c. 2450	$10^4 - 10^7$
Rhyolite	700 – 900	c. 2200	$10^9 - 10^{13}$
Komatiite	>1600?	c. 2800	<1?
Water at Earth's surface	20	c. 1000	10^{-3}
			*Newtonian approximation at low shear rate

Temperature °C (K)	Colour of Lava Surface
1150 (>1423)	White
1090 (1363)	Golden yellow
900 (1173)	Orange
700 (973)	Bright cherry red
600 (873)	Dull red
475 (748)	Lowest visible red

Field classification of lava flows

Crustal appearance provides the basis for classifying lava flows on land into three major categories, *pahoehoe*, *aa* and *blocky*. Pahoehoe and aa are Hawaiian terms introduced in the late 19th century to describe the common lava types found on Mauna Loa and Kilauea, but they apply equally to other lavas with silica contents less than about 50-55 wt% (basalts and some basaltic andesites), as well as to the rare flows of sulphur and carbonatite. Blocky flows are common among lavas with silica contents greater than 55 wt% (basaltic andesites to rhyolites).

Diagnostic features are most evident when viewing a crust over distances of decimetres and metres (Table 3; Figure 3). At these distances, pahoehoe surfaces are smooth and, though occasionally broken, are normally continuous, while aa surfaces are extremely irregular, frequently fractured, and usually covered by rough, contorted fragments with typical dimensions of centimetres and decimetres. Blocky lavas, like aa, also have fractured surfaces and a covering of debris; they differ from aa flows in that their fragments are smooth and angular with common dimensions from decimetres to metres. From a distance, indeed, both aa and blocky surfaces look as exciting as piles of rubble on a building site.

Aa and blocky flows

Aa and blocky flows show simple evolutionary trends. As might be anticipated from their broken surfaces, their fronts tend to advance as single units and it is rare for one part of a front to move far ahead of neighbouring sections. Blocky fronts crumble to produce a snout of debris from the early stages of emplacement. Aa fronts show a greater range of behaviour, often starting as fluid sheets, but finishing as near-solid masses that fragment throughout their thickness to maintain advance; between these limits, they move by various combinations of fracture and flow.

Fronts thicken while advancing, often growing to more than ten times their initial thickness. Final thicknesses are typically about 20 m or less for aa fronts, but several tens of metres for blocky flows; their maximum lengths are measured in tens of kilometres and in kilometres, respectively. Major flows can achieve volumes of 1-100 million cubic metres, and tend to be emplaced within days when they are aa but within months when they are blocky.

Table 3. Common Features of Flow Surfaces

Feature	Description
1. Aa Lava	Surface is covered by a jumble of irregular crustal fragments.
Cauliflower	Crust twists upwards as cauliflower-like protrusions. These break to give fragments up to decimetres across. Surfaces are grey-black, often glassy, and rough and spinose at the millimetre scale.
Rubbly	Crust fractures downwards to yield rounded rubble up to metres across, often with an ochre-black granular surface, millimetres deep
2. Blocky Lava	Surface is covered by broken lava, containing fragments up to metres across with smooth, planar, and angular surfaces.
3. Pahoehoe Lava	Surface is smooth and continuous, often with a millimetre-scale texture of interweaved lava threads or filaments.
Entrail	Dribbles of lava yield convoluted surfaces reminiscent of entrails.
Ropy (or corded)	Flexible crusts ruck into tight folds before chilling. Surface resembles segment of coiled rope. Each "rope" can be centimetres thick.
Shelly	Highly vesicular, fragile crusts. Often associated with skins, centimetres thick, over hollow lava blisters. The skins break underfoot, giving the impression of walking on egg shells.
Slabby (sometimes slab aa)	Slabs of broken crust, up to metres across and centimetres thick.
4. Toothpaste Lava	Protrusions of viscous lava squeezed through gaps in flow crust. They may be tens of metres long and their cross-sections often mimic the shape of the source gap, like toothpaste emerging from its container.

Both flow types initially develop channels to feed lava to their fronts. Channels form when a flow stops widening and concentrates motion downhill. The fronts themselves grow during advance because they decelerate as they solidify and allow faster lava to accumulate from upstream. For example, during the opening stage of emplacement (when they are fastest), major aa fronts may advance a few kilometres a day (occasionally 10-30 km in the first 24 hours), although the velocity of lava near the vent may be at least ten times greater.

At one extreme, advance and thickening continue until a flow stops being fed by new lava, whereupon the front slows to a halt as remaining lava drains from the feeding channel. At the other extreme, effusion continues into the flow even though the front has come to rest. Lava begins to pile up within the channel, starting at the front and working its way backwards. As it thickens, the channel lava exerts an increasing pressure on its margins, and these may eventually breach to form an outlet through which the channel lava can escape. If the breach is too small, it may be able to heal itself through cooling or by being plugged with crustal debris. Otherwise, the breach may become a permanent outlet from which a major new flow can develop. The new flow, in turn, may halt and thicken until the cycle is repeated. In such a way, a *flow field*, the final product of one effusive eruption, may evolve with time from a single flow to a collection of interconnected flows (Figure 4).

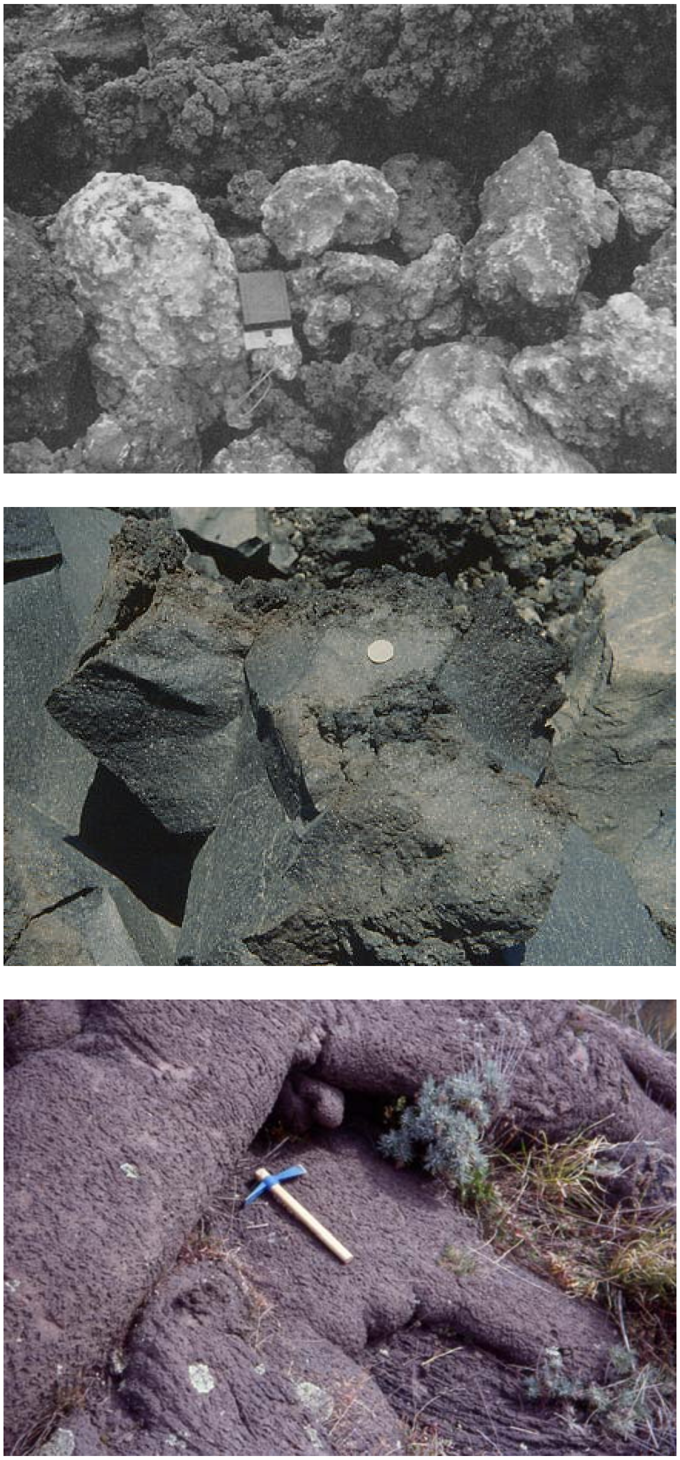


Figure 3. The surfaces of aa and blocky flows are covered by broken surface fragments.
(Top) Aa fragments (Mt Etna, Sicily) are contorted and initially appear black and spinose *(top)* but, during later stages of advance, the surface breaks to yield rounded and abraded rubble *(bottom)*.
(Middle) Blocky fragments (Nea Kameni, Santorini, Greece) are angular and have planar faces.
(Bottom) Pahoehoe surfaces (Vesuvius, Italy) are smooth and often billowy over distances of metres. (Photos: (*Top, Middle*) C.R.J. Kilburn; (*Bottom*) S. Black).

Breaching is more common among aa than blocky lavas. Apart from high channel pressures, the propagation of new flows by breaching requires channel lava that is much more fluid than its lateral margins. Only in this case can the channel lava easily escape through a breach; if, instead, the channel lava is almost as solid as the margins, breaching simply allows channel lava to spread into the breach and heal it. By virtue of its chemical composition, channel lava in aa flows tends to be more fluid than its blocky equivalent, so that conditions are more favourable in aa lavas for the propagation of new flows.

Although breaching may occur anywhere along a flow, it most commonly occurs somewhere along the upstream half of a flow's length. Newly-propagated flows may extend downslope beyond an earlier stream, but rarely do they increase the length of a whole flow field by more than half the length of the initial flow. A result of such behaviour is that the propagation of flows tends to widen, rather than to lengthen, the area covered by new lava (Figures 4 & 5). It also means that, when addressing the hazard from aa and blocky flows, the first goal is to estimate the probable maximum length of the *initial* flow.

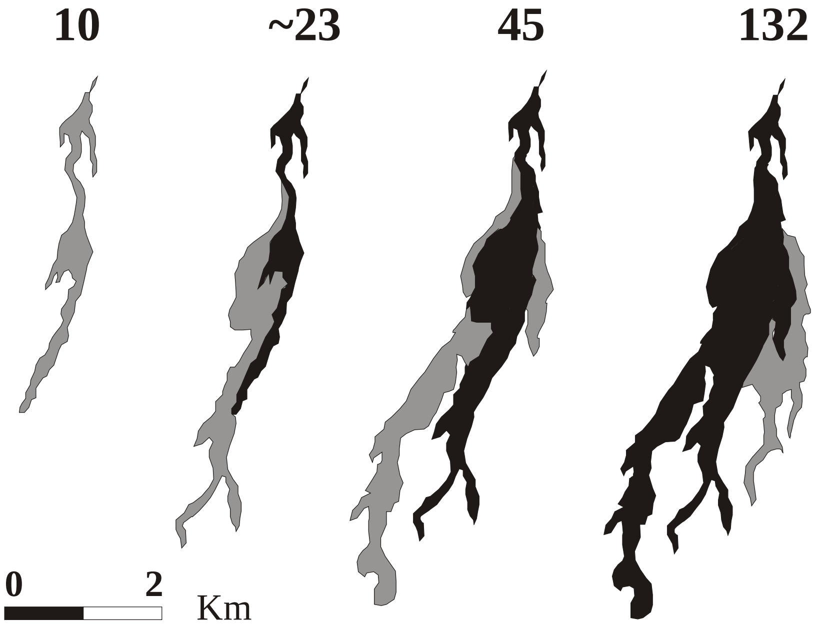


Figure 4. Aa flow fields grow as propagating a sequence of flows, new flows (grey) propagating from the sides of earlier streams (black). This example shows the evolution of Etna's 1983 flow field at 10, 23, 45 and 132 days after the start of effusion. Note how the final length of the flow field on Day 132 is only about 30% greater than the length of the initial flow on Day 10. (Data from Frazzetta and Romano 1984).

As well as promoting flow breaching, flow thickening can trigger the overflow of fluid channel lava across its lateral margins. The margins can thus build themselves up as a series of superposed overflows which, under favourable conditions, develop an inward overhang across the channel surface. As the exposed channel surface narrows, it becomes easier for adjacent segments of crust to congeal together and to form a continuous roof over the flow. In this way, a lava channel can evolve with time into a tube, better insulating the lava beneath and allowing it to travel further before solidification sets in.

Tubes form in aa and blocky flows only after a channel has become well-established, and may require several weeks to develop. When they occur, therefore, tubes are found along those parts of flows which remained active for long periods, typically behaving as feeders to sites of breaching downstream. As a result, tubes normally form after most major flows have been emplaced, and so rarely contribute in a significant way to extending a flow field (in complete contrast with pahoehoe flows, discussed below). As with the propagation of flows by breaching, the growth of lava tubes is favoured by a large contrast between the fluidity of internal lava and its external margins. Accordingly, tubes are more common in aa than in blocky flows. Should lava drain from a tube towards the end of effusion, it may leave behind a tunnel perhaps kilometres long that is large enough at least to crawl through. Among aa lavas, excellent examples can be found on Sicily's Mt Etna, including the 1971 and 1991-93 flow fields.

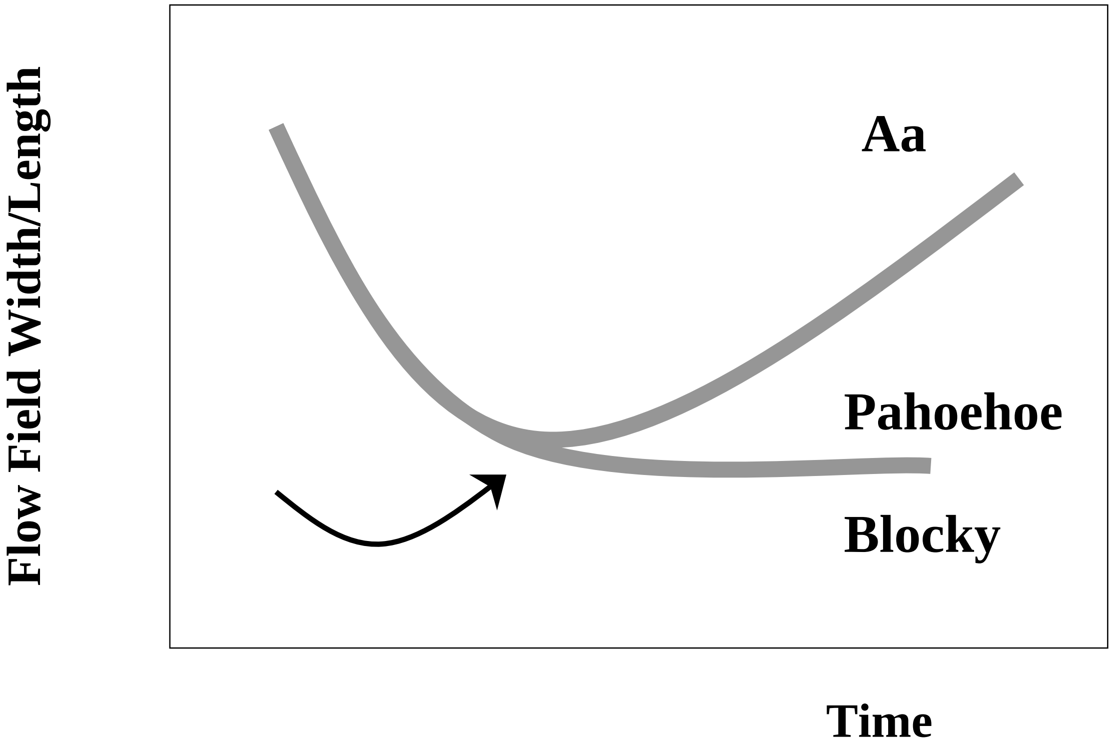


Figure 5. All flows initially lengthen so that their ratio of width to length decreases with time. This trend normally continues throughout eruption for pahoehoe and blocky flows. After the first flow is emplaced *(arrow)*, aa flow fields tend instead to become wider. The initial flows rarely lengthen for more than 10-15 days. For all lava types, major flow fields are normally emplaced within months-years, although some historical effusions (especially of pahoehoe lava) have continued intermittently for a decade or more (*e.g.*, Etna, 1614-24; Pu'u O'o, Kilauea, continuing since 1983).

Pahoehoe flows

Pahoehoe flows have dimensions similar to aa flows, but normally advance at least ten times more slowly. Because they spread slowly, their cooling surfaces resist extensive tearing and, though feeding channels can develop, it is not unusual for continuous crusts to form across a whole flow from the start of emplacement (unlike the weeks necessary in the case of aa lavas). The crust remains continuous around flow margins and fronts, whose initial thicknesses are usually of only a few decimetres. Since early flows are thin, they are easily retarded by the crust and spreading occurs by a combination of lava leaking out as small tongues through breaks in the crust, and by allowing new lava from upstream to burrow beneath the tongues and to slowly lift the front upwards. The front thus appears as a collection of intermingling tongues, each much narrower (by 10-1000 times) the width of the whole flow (Figure 1).

Pahoehoe tongues may extend by some 100 m, and even start to develop feeding channels, before crusting over and extruding small lava toes, typically a few metres or less in length (analogous to the lava pillows among submarine flows). As a result, pahoehoe fronts and margins soon develop as a complex of budding tongues and toes, all of which are gently uplifted by newly arriving lava. The surfaces of pahoehoe flows thus evolve a curious hummocky form, involving swells that extend distances from decimetres to hundreds of metres. The largest of these seem almost flat to the casual gaze; the smallest appear curiously grotesque and intestinal (Table 3).

Lava from the vent continually raises the surface and, within weeks, a flow field may have thickened to several metres, while thin lava tongues continue to emerge from around its edges and from occasional surface ruptures. Although many tongues and toes stagnate after halting, others remain connected beneath the crust to form a network of distributary tubes, casually resembling an underground river system. Compared with the open channels in aa and blocky flows, lava tubes reduce the rate of lava cooling, especially when they are partly drained so that hot gases can collect beneath the tube roof and keep the flowing lava surface at temperatures close to its initial value. Thus, although pahoehoe flows advance more slowly than their aa counterparts, their interiors remain fluid for much longer periods. The greater lengthening time often dominates the slower velocity, so that pahoehoe flow fields can achieve lengths greater than aa flow fields of similar volume.

Historical pahoehoe flow fields have extended several tens of kilometres, the best examples being found on the Big Island of Hawaii. Some prehistoric flow fields, however, have been traced for more than 100 km, notably those in Queensland, Australia. Recently, it has been proposed that ancient flood basalts (such as the Columbia River Basalts in the U.S.A.), which have lengths of several hundreds of kilometres, are in fact enormous pahoehoe lavas, and not extreme aa flow fields as previously thought. The drained tube systems in such flows are truly impressive, reaching tens of metres across, up to 10-20 m high, and extending for several kilometres at least (the prehistoric Australian flow fields contain a tube system about 100 km long).

The lava spectrum

In the simplest of cases, a flow maintains the same type of surface morphology throughout emplacement. Frequently, though, a flow surface evolves through more than one type with distance downstream. Among basaltic lavas, downstream transitions occur from pahoehoe to aa morphologies, while the change from aa to blocky is found among some basaltic andesites; both transitions are unidirectional, so that blocky surfaces do not become aa, and aa surfaces do not become pahoehoe (although, as discussed later, special field conditions may give the false impression that reverse transitions can occur). The pahoehoe, aa and blocky morphologies are thus not independent entities, but parts of a continuous spectrum of lava types. The association of the two transitions with different lava chemistry shows that composition is one underlying control. However, since each transition occurs between lavas of similar composition, other non-chemical factors must also be involved.

Both pahoehoe and aa surfaces are created during the formation of surface crust. At the start of eruption, the lavas are often too fluid to break before cooling, so that the degree of rupture must be controlled by the solidifying surface layers. To break a surface before it has chilled to its maximum strength, the rate of energy supplied predominantly by gravity to a unit volume of crust must be greater than a critical value. The critical value depends on how quickly a crack can be healed by chilling the newly-exposed lava beneath. If the critical value is exceeded, a flow breaks its crust more quickly than existing cracks can be healed and so evolves a fragmented aa surface; otherwise, a flow cannot tear its crust quickly enough and develops a continuous pahoehoe surface.

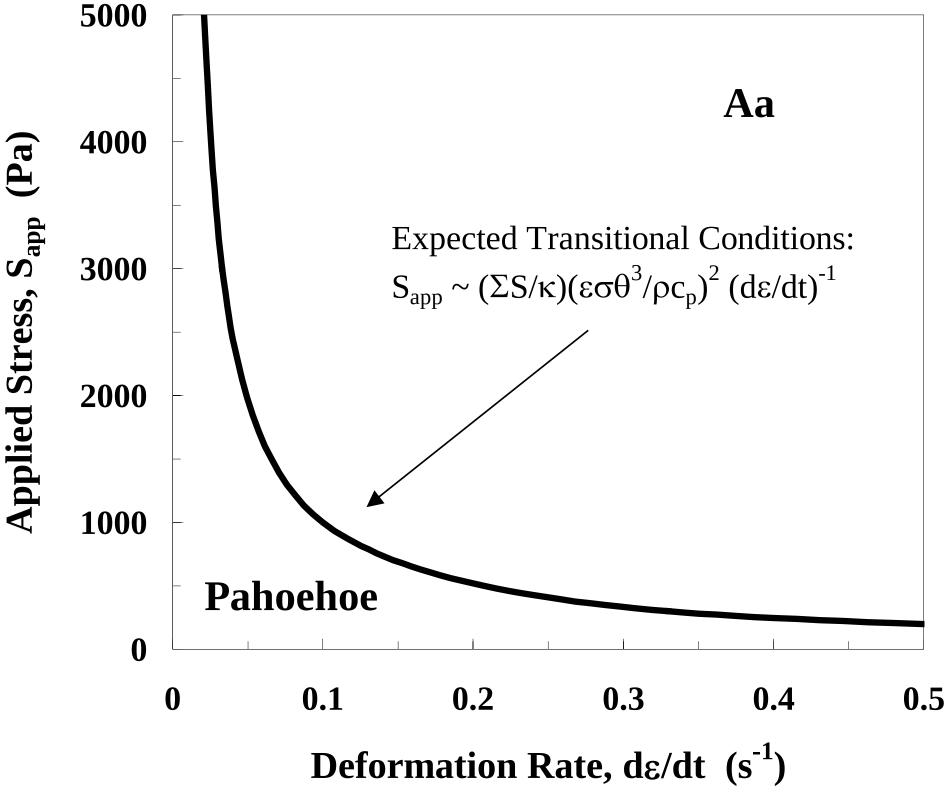


Figure 6. The evolution of pahoehoe and aa surfaces depends on the rate at which energy is supplied to deform cooling crust. The rate of energy supply per unit volume is given by the product of applied stress and deformation rate (S_{app} dε/dt). Below a critical energy flux (~100 J m^{-3}) controlled by the cooling and strengthening of lava exposed between cracks), the surface chills as a continuous crust to form pahoehoe. When this flux is exceeded, the surface breaks persistently to form aa. Blocky lavas are not shown on this diagram, because they are strong before eruption and, as if magmatic glaciers, they must break their surfaces to advance, independent of cooling effects.

The rate of energy supply is measured by the product of the stress applied to the crust and the rate at which the crust deforms (Figure 6). Two consequences are that the larger the pull, or applied stress, the smaller will be the deformation rate at which critical conditions are reached; and to cross the pahoehoe-aa transition, the rate of energy supplied (per unit volume) to the crust must also increase. The change from pahoehoe to aa occurs because, as lava advances downstream, a greater proportion of the gravitational energy flux for moving the whole flow is used in deforming a thickening crust. Eventually, the energy flux exceeds the critical value, after which the surface must break persistently as aa if the flow is to advance.

Blocky surfaces are associated with stronger and more viscous lavas that break before cooling is significant. In this regard, they can be considered magmatic glaciers, slowly-moving sheets that flow near their bases but break at their surfaces. The aa-blocky transition thus occurs when the lava interior becomes too crystalline to move forward only by flowing, so that surface fracturing is no longer controlled by crustal cooling. Indeed, the same reasoning explains why pahoehoe and blocky lavas have different surface morphologies, even though both advance much more slowly than aa flows; blocky flows are slow because of their high viscosity and break because of their large associated strength; pahoehoe flows are slow because they advance as thin sheets or tongues whose fluid interiors are easily restrained by surface crust.

The transitions between surface morphologies are irreversible; highly fragmented surfaces cannot recombine to form continuous crust (hence aa surfaces do not evolve into pahoehoe), while subcrustal lava does not become less solid with time (hence blocky surfaces do not evolve into aa). On occasion, however, it might *appear* that a reverse transition has taken place, especially between pahoehoe and aa types. The deception occurs under two main sets of conditions. The first corresponds to changing conditions of effusion from the vent. As an eruption decays to its close, so also decreases the rate of effusion. While early, fast lava may produce an aa surface, later lava may emerge slowly enough to form a continuous pahoehoe crust (good examples can be found on Mauna Loa, Hawaii). This change, though, does not represent a transition from aa to pahoehoe, since the later pahoehoe crust formed across an independent flow and did not evolve from lava already erupted with an aa surface. The second condition involves the escape from aa channels of hot internal lava, the result either of a channel overflow or of a margin being breached. In this case, the escaping lava may be less crystallized and, if advancing much more slowly than the parent flow, may form a pahoehoe crust. Once again, such a situation does not correspond to an evolution of the crust from aa to pahoehoe, because the escaping lava comes from deep within the parent flow and has had a crystallization history independent from that of the near-surface lava layers which formed the earlier crust.

Lava dynamics and internal solidification

Because of its high viscosity, lava can rapidly reduce accelerations in a flow. As a result, flows tend to settle into a steady dynamic state. A simple example is shown by the preference of flow fronts to advance at nearly-constant velocities for extended periods of time (Figure 7). Since inertia is not important, flow growth is controlled by how a lava's rheological resistance is overcome by gravity (pulling lava downslope) and by pressure differences due to local variations in flow thickness (notably at the flow periphery).

Another consequence of low inertia is that lava strives to maintain laminar flow, whereby adjacent packets of lava tend to flow past each other, rather than intermingling, as would occur if motion were turbulent (although turbulence may be important in some exotic lavas, discussed later). Without intermingling, a lava interior can diffuse heat only by conduction (*i.e.*, interactions between neighbouring molecules), so that cooling effects tend to migrate inwards from the flow exterior, itself maintained at a low temperature by radiation to the atmosphere, by cooling wind, and by precipitation. Lava, however, is a very poor conductor. The time needed for cooling to penetrate a depth D into a flow is given approximately by $D^2/4\kappa$, where the thermal diffusivity (κ) of lava is bewteen 10^{-7} and 10^{-6} m^2 s^{-1}. Thus it takes minutes to chill a layer centimetres deep, but weeks for this layer to thicken to metres.

To give an example of a lava flow 10 km long, the time for lava to travel from the vent to the front may be only hours for pahoehoe and aa flows, and days for blocky flows (Recall that this travel time is less than the interval since effusion began: the former is given by [flow length]/[mean velocity *along a flow*]; the latter is [flow length]/[mean velocity *of the flow front*].) The corresponding mean flow thicknesses will be measured in metres or tens of metres, implying conductive cooling times of weeks or longer. It might thus be expected that the interiors of pahoehoe and aa flow fronts will contain lava almost as fluid as it was near the vent. This condition is typical among pahoehoe flows, but not so for aa flows, which can develop solidified fronts within days.

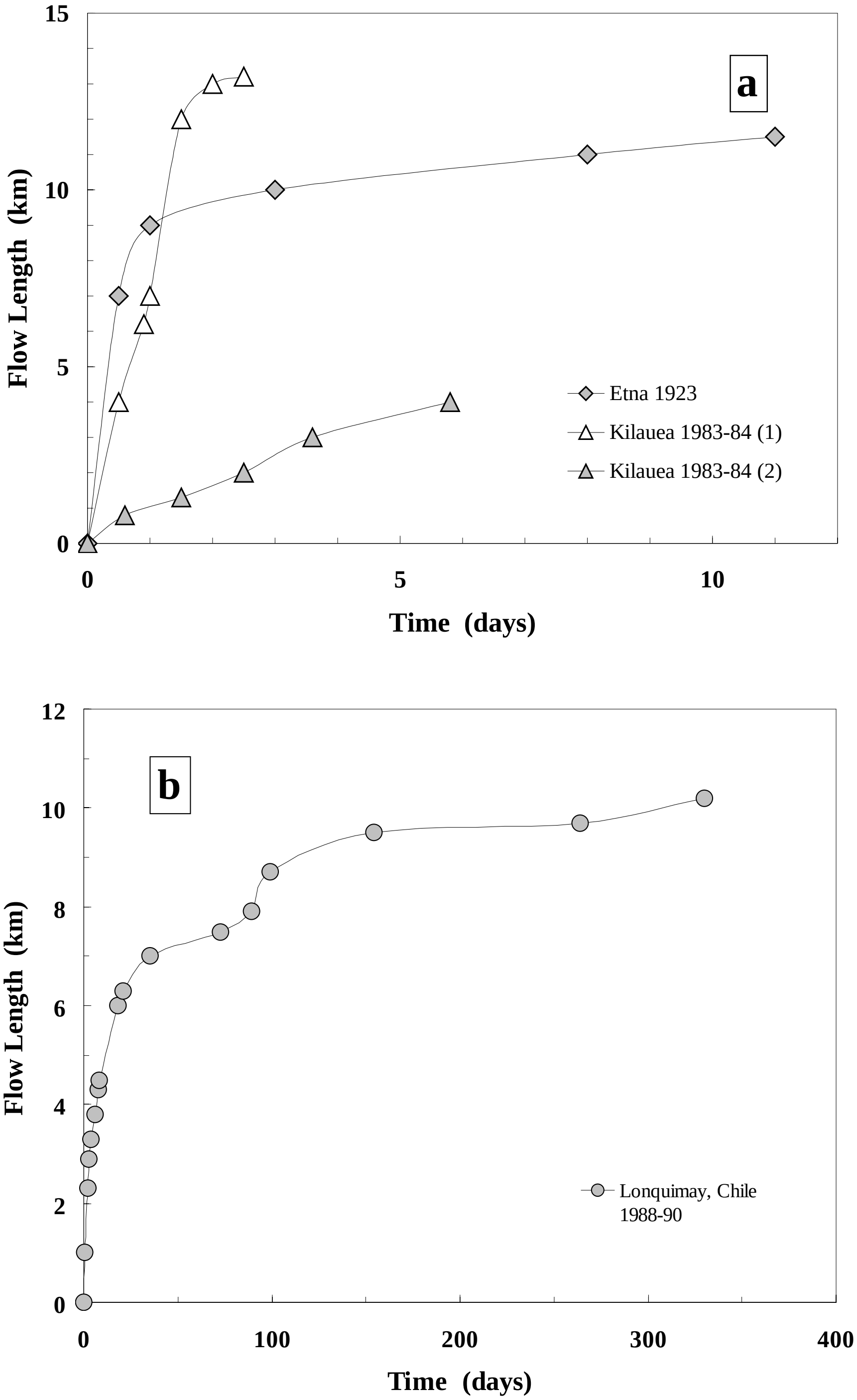


Figure 7. Most flow lengthening occurs during the early stages of effusion and at nearly constant rates of advance. This may be followed by a rapid drop in advance rate which, though continuing for a long time, does not extend a flow significantly. (Data from: (*a*) Ponte 1923, Wolfe et al. 1984; (*b*) Naranjo et al. 1992).

Precisely why the interiors of aa flows can solidify so quickly is still not fully understood. One possibility is that, compared with other lava types, aa lavas are initially richer in volatiles. All magmas contain some volatiles, mostly water, that remain dissolved at depth, where the high pressure from surrounding rock prevents them from forming bubbles. As the magma ascends, the imposed pressure decreases and, eventually, bubbles can develop, just as they appear in a bottle of soda water when pressure is released as the bottle is opened. The loss of volatiles upsets the chemical balance in the liquid and can trigger crystallization at a rate that increases with the proportion of gases originally dissolved in the magma, but decreases with increases in liquid viscosity. Thus, compared with aa lavas, pahoehoe interiors may crystallize more slowly due to smaller amounts of initial gas, while crystallization in blocky interiors is retarded by high lava viscosity.

Another explanation appeals to crustal entrainment. Pieces of cold crust are dragged back into the lava interior, accelerating solidification by forcing internal lava to intermingle. Importantly, the intermingling in aa is a result of crustal entrainment and not of natural turbulence; when possible, the flow again seeks a simple laminar motion. This mechanism is less common in pahoehoe flows, since they form continuous crusts, and also in blocky flows, because their very large viscosity impedes incorporation of surface debris

Shapes of lava flow margins

As they negotiate topographic irregularities and adjust to local variations in physical condition, lava flows are rarely able to spread evenly over the ground and so usually develop margins with irregular outlines. The degree of margin irregularity varies with flow type and, since all types can evolve over similar topography, such variation must reflect differences in style of advance and, hence, also in the governing force balance.

Spreading as collections of tongues and toes, pahoehoe flows develop lobate margins whose degree of unevenness (measuring fluctuations about a smoothed, average outline) happens to be similar for averaged outlines at least 1-100 m in length. Such a scale-independent (fractal) unevenness suggests that pahoehoe spreading is governed by the *ratio* (scale independent by definition) of imposed forces, and that these forces are of the same type at each scale. Since crustal restraint is essential to the pahoehoe style of advance, the obvious inference is that, whatever their size, tongues and toes propagate when, given sufficiently fluid internal lava, the forces driving lava spreading exceed crustal resistance by only a critical amount; otherwise spreading would cease (driving forces too small) or the crust would fragment and have no significant resistance (driving forces too large).

In contrast, aa and blocky flows spread mostly under conditions for which the driving forces are far greater than crustal resistance. Thus, although locally influenced by crustal debris, the bulk shape of their margins is more dependent on the rheological resistance of internal lava. As a result, the margins appear highly irregular over distances covering a few crustal fragments (notionally 10 m or less), but tend to show only subdued undulations over 100 m or more. Hence the shape of the flow outline is not scale-independent, but becomes less uneven as the measuring distance becomes larger, coinciding with a change in the chief shape-controlling factor from the geometry of crustal fragments to bulk lava rheology.

The connection between flow type and margin geometry opens the possibility of using geometric measurements to infer styles of lava emplacement, especially important for investigating inaccessible volcanoes with aerial and spaceborne techniques. However, apart from initial measurements on predominantly basaltic lavas, few data are available on the fractal dimensions (degrees of unevenness) of lava flow margins, and so the full promise of this approach must await future studies.

Forecasting the behaviour of aa flows

The three main types of lava surface are associated with distinct styles of flow growth. Since lava surfaces are easily monitored in the field, it would be convenient if the conditions for producing a specific surface type could also provide limits upon the likely distance and velocity a given flow might travel. Such a state of affairs does exist for aa flows, a happy circumstance since aa flows are the lava type that has most frequently threatened human activity, and they are also intermediate between pahoehoe and blocky flows. Understanding the limits to aa behaviour thus provides clues to the limiting behaviour of the other flow types.

The aa surface criterion can be used to estimate the advance velocity needed to keep breaking lava crust. The time for which a lava flow can continue to advance is controlled either by the duration of eruption (for short-lived aa flows) or, during long eruptions, by the time needed for the flow to acquire a solid front. Combining the requirement for a lava front to solidify (which gives the longest time for advance) with the aa surface criterion, it is possible to link the *maximum* potential length (L_m) of an aa flow to lava properties, mean underlying slope (angle β) and mean rate of discharge (Q). These expressions are:

$$L_m \approx [(1.5\ \varepsilon S/\rho g)^2\ (\Sigma\sigma\Theta^3)/(\kappa\rho c_p)]/\sin^2\beta \tag{1}$$

$$L_m \approx [3\varepsilon S/\rho g\kappa]^{1/2}\ Q^{1/2} \tag{2}$$

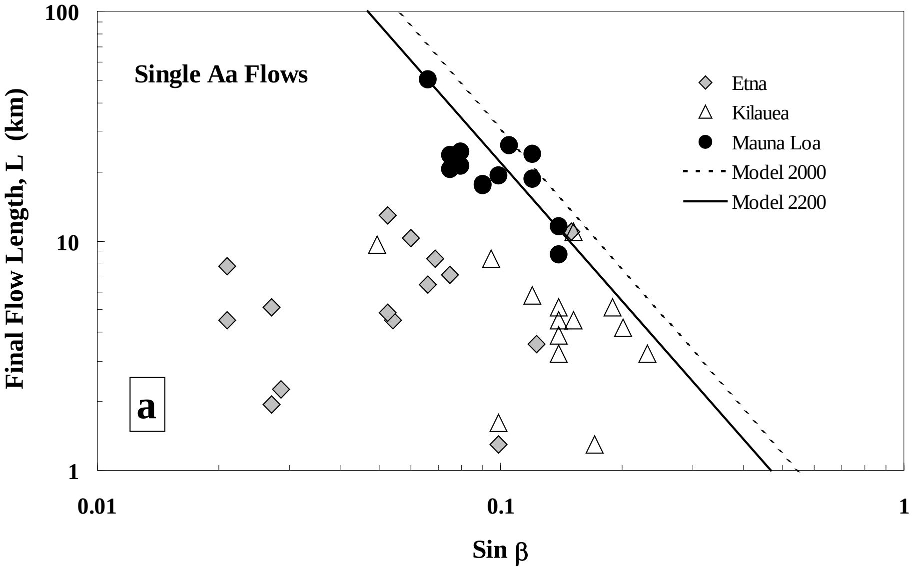
where the remaining symbols are defined in Table 4.

In both expressions, the terms in square brackets describe the physical properties of the lava crust and are approximately constant for a given lava composition. Thus the maximum potential length is expected to increase as the mean underlying slope decreases (Equation (1)) and as the discharge rate increases (Equation (2)), two trends which agree well with observation (Figure 8).

Table 4. Parameters in Flow Equations

Symbol	Meaning	Units	Nominal Value for Basalt
β	Slope angle	°	
c_p	Specific heat capacity	$J\ kg^{-1}\ K^{-1}$	1150 (during crystallization)
D	Thickness	m	
ε	Extension before failure	-	min. 10^{-3} (for chilled crust)
εS	Energy per unit volume for failure	$J\ m^{-3}$ (or Pa)	2×10^4 (during crystallization)
g	Gravitational acceleration	$m\ s^{-2}$	9.81
κ	Thermal diffusivity	$m^2\ s^{-1}$	4.2×10^{-7}
L_m	Maximum potential length of flow	m	
Q	Mean discharge rate along flow	$m^3\ s^{-1}$	
Θ	Eruption temperature (absolute)	K	1350 - 1400
ρ	Density of lava crust (not whole flow	$kg\ m^{-3}$	2200 (~20% vol. vesicles)
S	Tensile strength	Pa	max. 10^7 (for chilled crust)
Σ	Surface emissivity	-	1
σ	Stefan-Boltzmann Constant	$J\ m^{-2}\ s^{-1}\ K^{-4}$	5.67×10^{-8}
t	Time	s	

The length-slope trend is counter-intuitive. Other factors being equal, it might be supposed that steeper slopes would favour longer flows. The inverse trend arises because, to keep breaking their surfaces, aa flows must maintain greater thicknesses on shallower slopes. Thicker flows need longer times for their fronts to solidify. As a result, the maximum *potential* length increases with decreasing slope. In practice (Figure 8), such lengths are usually not achieved (especially on slopes with angles smaller than 6°) because the eruption finishes or breaching occurs in the meantime. Nevertheless, the length-slope trend is important for hazard analyses because it provides realistic estimates of potential flow length when only the mean slope is known. Accordingly, it is well-suited for preparing hazard maps before an eruption occurs.



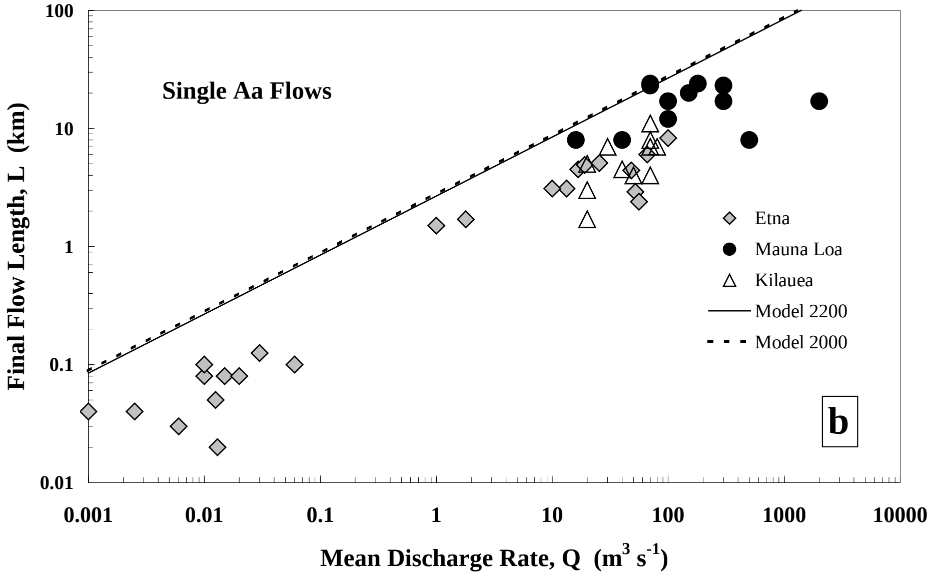


Figure 8. The conditions that (1) aa surfaces must break before they cool to their maximum strength and (2) flow fronts advance until solidified yield criteria for relating the maximum potential length of a single aa flow to *(a)* underlying slope (sinβ) and *(b)* rate of discharge (Q). These criteria (Equations (1) & (2)), shown by the solid and dashed trends, agree well with observations from Etna and Hawaii. The solid and dashed lines refer to respective mean crustal densities of 2,200 and 2,000 kg m^{-3}.

The length-discharge rate trend may also have predictive value in some special circumstances. At several mature effusive volcanoes, the mean rate of lava effusion generally decreases with increasing altitude of the vent. Equation (2) can therefore be modified to link maximum potential flow length to vent altitude, shorter maxima being associated with higher elevations. Pre-eruptive maps of lava hazard can thus be prepared on the basis of vent elevation, and these provide a useful check on evaluations determined from mean slopes.

Equation (2) may also be used for short-term forecasts while an eruption is in progress. During the 1991-93 effusion on Etna, for example, secondary aa flows began to overtop an artificial barrier and descend toward Zafferana, a town almost 3 km further downslope. Initial observations suggested that it was unlikely for the mean discharge rate to exceed 1 m^3s^{-1} along any flow. From Equation (2), a maximum flow length of about 2 km was anticipated, indicating that the immediate threat to Zafferana was small. A forecast was issued to that effect and, in the event, the longest secondary flow travelled only 1.8 km beyond the barrier.

The success of Equations (1) and (2) is remarkable not only for the simplicity of their underlying assumptions, but also because they use mean values of slope and discharge rate to determine length. In reality, surface slopes are uneven, while discharge rate changes with time and position along a flow. The agreement between theory and observation thus suggests that local variations have normally a secondary effect on maximum potential flow length, so that mean values are sufficient for most purposes. Extreme variations, such as flow over a cliff or through a very narrow ravine, may induce significant changes from the model results and, until more sophisticated analyses are available, these rare cases must be evaluated individually.

The expressions for maximum length assume that an aa flow travels until its front has solidified. The maximum time t required is

$$t \approx [(\varepsilon S/\rho g)(\rho c_p/\Sigma\sigma\Theta^3)^{1/2}]/\sin\beta \qquad (3)$$

As before, the combination of physical properties (Table 4) in the square brackets is roughly constant for a particular lava composition and, for typical angles of 2°-10° for the slopes of basaltic volcanoes, yields lengthening times of about 1-10 days (the longer times corresponding to smaller slopes). During a long-lived eruption, therefore, major breaching and the propagation of new flows is most likely to commence within days following the start of effusion. Since new flows rarely extend a flow-field by more than half the length of the first major flow, another forecasting problem is to assess the final width of a flow field, which may stretch to several kilometres.

An aa flow field can widen until halted by topography or by the end of effusion. The topographic control depends on local conditions and must be assessed on a case-by-case basis. The likely duration of an effusion can be estimated by comparison with previous eruptions, but even on well-studied volcanoes, such as Etna, Kilauea and Mauna Loa, such estimates are rarely better than inspired guesswork. Improvements will follow when it becomes possible either to estimate (probably by geophysical monitoring) the quantity of magma below ground that is available for eruption, or to forecast the long-term decay in rate of effusion as an eruption proceeds.

Forecasting the behaviour of pahoehoe and blocky flows

It is possible before an eruption to estimate the maximum length of an aa flow because the surface criterion provides a velocity, and the solidification control yields a time. Such a combination is not available either to pahoehoe or to blocky flows and so forecasts of their growth is inherently more difficult.

For pahoehoe flows, the requirement to form a continuous crust can be used to constrain maximum rates of advance to about 1 km per day on slopes typical of basaltic volcanoes.

Unfortunately, the burrowing mechanism, by which new lava intrudes into the front after travelling through insulated tubes, has so far defied realistic estimates of maximum cooling times. As it happens, observed pahoehoe flows (mostly from Hawaii) have frequently lengthened for the whole of an eruption, even when this has continued for several months (Figure 5). In practice, therefore, pahoehoe emplacement is often limited by the available supply of magma, and so forecasting flow behaviour is subject to the same problems encountered when estimating the final width of an aa flow field.

Among blocky lavas, surface fracturing appears to be controlled by the strength of lava beneath the chilled crust. As a result, fracturing is not required to be faster than the rate of surface chilling, and so no surface criterion is available for forecasting mean rates of advance. Velocity forecasts must therefore rely on knowing the rheological state of a lava and the rate at which it is effused, factors which can be estimated by analogy with previous effusions from the same volcano.

Since the lava is viscous and slow moving, a blocky front is expected to solidify at a rate controlled by conductive heat transfer to the breaking surface. From standard conduction theory, a crude estimate of the solidification time for common final thicknesses of 10-30 m is from six months to over four years, lengths of time that are greater than the usual durations for eruptions of blocky lava. Once again, the volume of magma available appears crucial for determining how far a lava can travel, and estimating this volume remains a fundamental obstacle to improving pre-eruptive forecasts of blocky flow growth.

Turbulent lava flows

Lava flows witnessed in historical time have had physical characteristics that favour laminar motion, and so it is this motion which has been assumed in developing quantitative models of lava behaviour. However, some ancient lavas on Earth, erupted for the most part more than 2,500 million years ago, may have been sufficiently fluid upon eruption for turbulent advance. Turbulent flow involves the spontaneous intermingling of neighbouring packets of lava, so that internal lava cools and solidifies more quickly than would have been the case for simple laminar flow. The net result may well have been the persistent surface disruption of a lava undergoing wholesale internal solidification, analogous to conditions for aa lava flow emplacement (for which, as discussed above, internal solidification is induced by factors other than spontaneous turbulence).

Notable candidates for ancient turbulent flows are komatiite lavas (Table 2) which, named after their discovery near the River Komati in South Africa, are found dotted across the world's oldest continents (Africa, Australia, and North and South America) and are often associated with economically important nickel deposits. Essentially basalts with unusually large amounts of magnesium, iron and aluminium, these lavas since their eruption have been buried by younger material and grossly deformed by major changes at the Earth's surface. As a result, it has not been possible to investigate directly the influence of turbulent motion on lava flow morphology. This is unfortunate, since interest has been generated by speculation that komatiites could be among the types of lava flow observed on other planets. Only when direct chemical analyses are available for extraterrestrial flows will it be possible to gauge the potential signifance of turbulent flow on volcanoes beyond Earth.

Lava flows and planetary development

Lava flow fields are among the commonest surface features of the terrestrial planets. Quite apart from hazard analyses, therefore, an understanding of flow emplacement is essential for investigating the evolution of planetary surfaces. By virtue of their remote location, most information on extraterrestrial flows concerns their dimensions and geometry. Especially impressive is the fact that flows stretching hundreds of kilometres are commonplace on the Moon, Mars and Venus, some exceeding the size of ancient flood basalts on Earth. Primary goals of planetary studies are to use flow shape and size to deduce chemical composition and to infer conditions in the magmatic feeding systems, thereby probing also into the states of planetary crusts and mantles.

Despite their large size, the shapes of planetary flow fields resemble those of their smaller cousins on Earth. Since flow shape depends on the ratios of controlling factors, geometrical similarity suggests that these factors remain within the same range of proportions to each other as they occur on Earth. It is thus realistic to assume that, unless extraterrestrial lava flows have been emplaced exclusively under turbulent conditions, the range of controlling ratios (*e.g.*, among the forces driving and resisting motion) found on Earth can be applied to the neighbouring planets and, hence, that extraterrestrial flows will also belong to the pahoehoe-aa-blocky spectrum.

Summary

Lava flows on land evolve along a small number of trends, each of which links surface structure to styles of advance and to modes of flow-field growth. These trends correspond to particular combinations of the forces driving and resisting flow motion. Fortunately, one combination (corresponding to aa lavas) provides the possibility for forecasting flow growth before an eruption has started. Unfortunately, emplacement of the remaining flow types, pahoehoe and blocky, appears to need prior knowledge of the amount of lava available, a quantity which it is not yet possible to assess before an eruption has finished. Remedies are expected as geophysical methods for investigating the insides of volcanoes become more sophisticated, so that a complete forecasting potential may be available beyond the Millennium.

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